Evolution of cdma2000 Cellular Networks: Multicarrier EV-DO

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ABSTRACT

The evolution of cdma2000 1xEV-DO systems to multicarrier EV-DO (supported by 1xEV-DO Revision B) is discussed in this article. Multicarrier EV-DO offers a backward-compatible upgrade to leverage existing 1xEV-DO networks and terminals. It allows a software upgrade to multicarrier EV-DO using 1xEV-DO Revision A base station hardware. Multicarrier 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. Multicarrier 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 article. It also enables hybrid frequency reuse deployment scenarios that enable spectrally efficient operation and significant improvement in edge coverage performance with hardware-efficient implementations. The evolved wider bandwidth systems (up to 20 MHz) based on multicarrier EV-DO offer operators a cost-effective solution that competes favorably with other technologies.

INTRODUCTION

Multicarrier 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 multicarrier operation, single-carrier terminals based on 1xEV-DO Release 0 or 1xEV-DO Revision A can operate on evolved EV-DO networks that support multicarrier 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 multicarrier EV-DO with expected publication in the first quarter of 2006. Multicarrier 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 multicarrier EV-DO-based services via software upgrade to 1xEV-DO Revision A channel cards. Multicarrier devices may operate in a single-carrier mode with 1x (IS-2000) or 1xEV-DO or a multicarrier mode of operation with two or more EV-DO Revision A carriers. Multicarrier EV-DO devices may support noncontiguous code-division multiple access (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]. We discuss fundamental multicarrier EV-DO concepts, and present the operator and end-user benefits of multicarrier EV-DO. We present some performance data and multicarrier EV-DO deployment scenarios followed by a summary.

FUNDAMENTAL CONCEPTS

Fundamental concepts introduced in multicarrier EV-DO are:

- Channel Aggregation via Multilink Radio Link Protocol (ML-RLP)
- Set management and adaptive server selection
- Symmetric and asymmetric modes of operation
- Multicarrier reverse link MAC
- Adaptive load balancing
- Flexible duplex carrier assignment

CHANNEL AGGREGATION

The Radio Link Protocol (RLP) is an automatic repeat request (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 multilink RLP, allows achieving higher peak data rates utilizing multiple carriers on the forward link using 1xEV-DO-Revision A channel cards. Multilink RLP is required when a terminal is assigned carriers on channel cards that do not communicate with each other and operate an independent scheduler.

As illustrated in Fig. 1, the base station controller (BSC) sends distinct packets to each of the assigned carriers (channel cards). The base transceiver subsystem (BTS) builds the packets and adds quick negative acknowledgment (NAK)

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

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(QN) sequence numbers to the segmentation and reassembly (SAR). Using the SAR sequence numbers, packets transmitted by a given channel card appear to have holes in sequence number space. In Fig. 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 NAKs as soon as it detects a hole in the SAR sequence number space. For example, 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. Multilink RLP therefore introduces a 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 the QN sequence number space on each individual link and the SAR sequence number to reassemble packets received on the separate links, as shown in Fig. 1. The SAR sequence number would be used by the terminal for reassembly 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 reassembly using the SAR sequence numbers allows multilink RLP to deliver packets in order to the higher layers. Non-contiguous QN sequence numbers indicate link erasures that are reported using RLP NAKs by the access terminal. Since the QN sequence number is not used for retransmissions, its length is required to be long enough to avoid wraparound 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 wraparound 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 retransmission, the retransmitted RLP packets do not need to carry the QN sequence number. It should be noted that multilink RLP is only necessary on the forward link and is not required when a single scheduler is responsible for scheduling transmission of packets across multiple carriers. From the perspective of the single scheduler that can schedule packet transmission across carriers, the additional carriers are analogous to additional interlaces on the forward link.

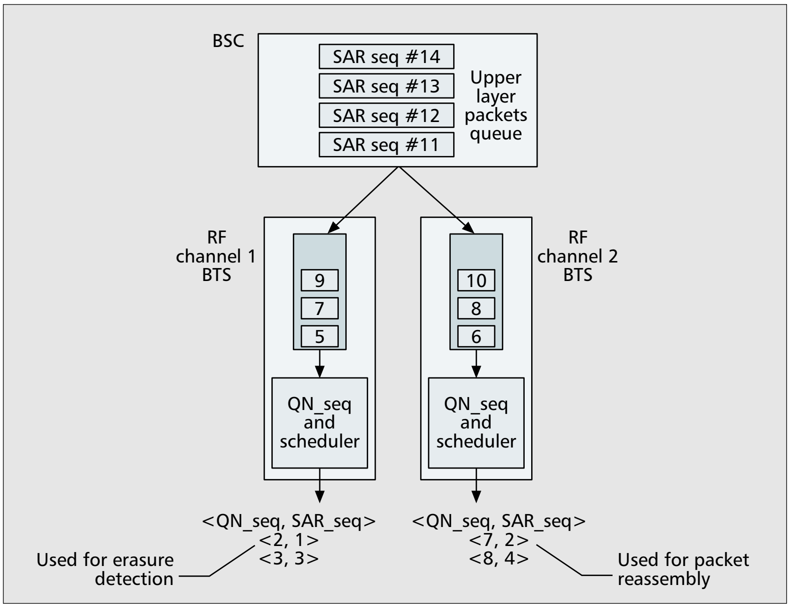

Figure 1. *Multilink RLP operation.*

SET MANAGEMENT AND ADAPTIVE SERVER SELECTION

A pilot in multicarrier 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 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.

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 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 collocated 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 Fig. 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 Fig. 2. The data source control (DSC) channel in multicarrier 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 multilink RLP with the different channel cards residing on different cells.

Multicarrier EV-DO supports symmetric multicarrier mode, basic asymmetric multicarrier mode, and enhanced asymmetric multicarrier mode.

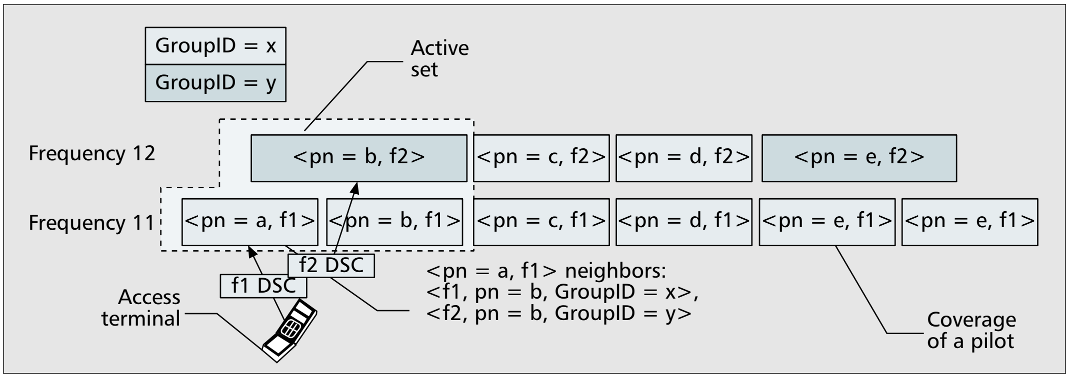

Figure 2. *Pilot GroupID assignment/coverage and DSC pointing.*

SYMMETRIC AND ASYMMETRIC MODE OF OPERATION

Multicarrier EV-DO supports the following three modes of operation:

- Symmetric multicarrier mode
- Basic asymmetric multicarrier mode
- Enhanced asymmetric multicarrier mode

In symmetric multicarrier 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 multicarrier mode enables multicarrier operation using aggregation of 1xEV-DO channel cards. If the access network hardware supports an asymmetric mode of operation, terminals would be set up in asymmetric mode for applications such as file download that require more bandwidth on the forward link than the reverse link. The 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 multicarrier mode a single reverse CDMA channel may carry feedback (data rate control [DRC] channel, acknowledgment [ACK] channel transmissions, and DSC channel transmissions) for more than one forward CDMA channel 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 four most siginificant bits (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.

The enhanced asymmetric multicarrier mode is similar to the basic asymmetric multicarrier 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 [9].

MULTICARRIER 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 (e.g., delay-sensitive flows) have high priority and are always permitted use of network resources up to a specified limit. Elastic allocation flows (e.g., best effort flows) use excess network resources once the demands of all fixed allocation flows have been met. In case of multicarrier 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 multicarrier 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.

To that extent, the access network can assign all carriers a terminal can support, which permits the terminal to transmit on the "best" carrier starting in the "best" time slot.

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 multicarrier transmission, which is discussed in the section on benefits of multicarrier EV-DO.

ADAPTIVE LOAD BALANCING

As in single-carrier systems, CDMA channel assignment in multicarrier 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 cooperative 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 the variable nature of application flows and bursty data sources, static load balancing cannot achieve uniform loading across carriers on shorter timescales. Adaptive load balancing can be achieved via cooperation 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 a terminal can support, which permits the terminal to receive packet transmissions on the "best" carrier starting in 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.

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 reallocate 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 deallocate 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.

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 [9]. Access terminals are typically designed based on fixed duplexer spacing. Examples of fixed duplexer spacing and flexible duplexer spacing are shown in Fig. 6, where deployment scenarios enabled by flexible duplexing are illustrated. 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.

BENEFITS OF MULTICARRIER EV-DO

Multicarrier EV-DO offers both operators and end-users significant benefits over that of single-carrier systems. Some of the benefits of multicarrier EV-DO are:
- Backward compatibility
- Reuse of existing infrastructure hardware, lower development cost, and rapid time to market
- Higher peak data rates, reduced latency and improved support for quality of service (QoS)-sensitive applications
- Improved transmit efficiency (reverse link)

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

[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 intercarrier spacing.

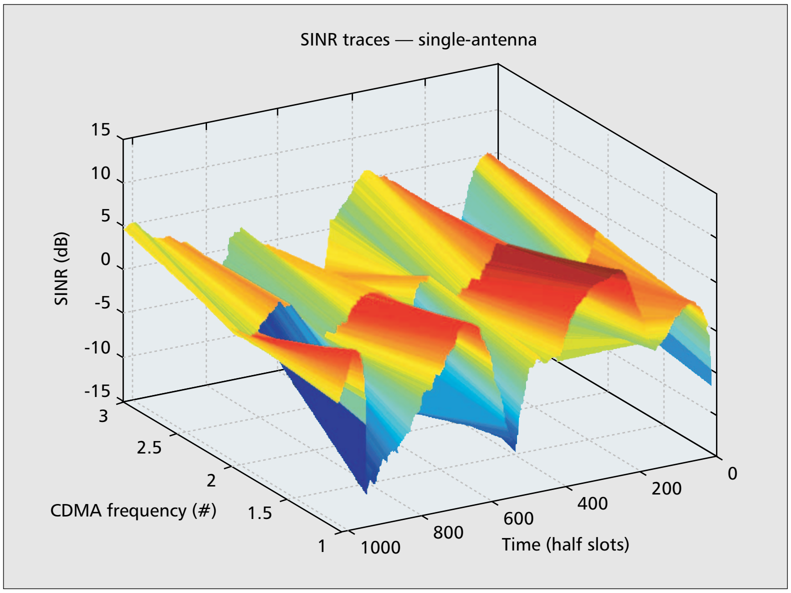

Figure 3. *Example forward link SINR trace in time and frequency domain for multicarrier EV-DO.*

- Higher spectral efficiency via exploiting frequency-selective fading across carriers
- Adaptive load balancing across carriers
- Alternate deployment scenarios due to use of flexible duplex assignment

IMPROVED TRANSMIT EFFICIENCY (REVERSE LINK)

The 1xEV-DO Revision A reverse link supports data rates from 4.8 kb/s to 1.8 Mb/s 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 LoLat 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 LoLat mode of transmission. For example, a single-carrier terminal can achieve 1.8 Mb/s by transmitting a 12,288-bit physical layer payload with a termination target of 4 slots. If the lower latency is not required, a multicarrier-capable terminal can achieve higher data rates without trading off spectral efficiency for delay. By transmitting a 12,288-bit payload on three carriers with a termination target of 16 slots, a multicarrier-capable access terminal can achieve a data rate (summed over all reverse link carriers) in excess of 1.8 Mb/s. The nominal data rate for 12,288-bit payloads over 16 slots is 460.8 kb/s, but a higher effective data rate is achieved by early termination due to physical layer hybrid ARQ (H-ARQ). A multicarrier terminal can therefore achieve higher spectral efficiency than a single-carrier terminal for delay-tolerant traffic.

IMPROVED SPECTRAL EFFICIENCY DUE TO CHANNEL FREQUENCY SELECTIVITY

Single-carrier systems such as 1xEV-DO exploit multi-user diversity in the time domain. Multicarrier systems such as EV-DO enable exploiting multi-user diversity in both 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 interfrequency channel correlation.

In order to evaluate the interfrequency channel correlation between adjacent CDMA channels, field tests were conducted on a 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-plus-noise ratio (SINR) is shown in Fig. 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 percent, which decreases with increasing channel spacing (60 percent for CDMA channels separated by one CDMA channel). Since sufficient channel decorrelation is achieved within 5 MHz of channel bandwidth, multicarrier terminals that support three carriers would be able to exploit most of the channel frequency selectivity.

PERFORMANCE

FORWARD LINK

Multicarrier 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 Third Generation Partnership Project 2 (3GPP2) evaluation methodology [2]. Support for multicarrier is added to the single-carrier evaluation methodology. The channel models are augmented for multicarrier assuming the same long-term fading across carriers in a multicarrier 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 multicarrier EV-DO, we use a proportional-fair (P-fair) scheduler, the equal grade-of-service (EGoS) scheduler, and the QoS scheduler modified to support multicarrier 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 indicator. We therefore define $DRC_{i,j}(n)$ as the channel state information from the access network to access terminal i on CDMA channel j in time slot n; $E\lfloor DRC_{i,j}\rfloor$ 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

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

[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.*

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 user i to maximize the metric

$$\frac{DRC_{i,j}(n)}{R_i(n)}.$$

The EGoS scheduler maximizes the metric

$$\frac{DRC_{i,j}(n)}{E\left[DRC_{i,j}\right]}\cdot\frac{1}{R_i(n)},$$

and the QoS scheduler maximizes the metric

$$\frac{DRC_{i,j}(n)}{E\left[DRC_{i,j}\right]}\cdot\frac{d_i}{R_i(n)}.$$

The analysis presented in this article focuses on channel model A (one-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/carrier/sector with the multicarrier simulations based on three carriers assigned to each access terminal.

Figure 4 shows the gains in sector throughput of a multicarrier 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 multicarrier 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 multicarrier 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 multicarrier 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 multicarrier 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.

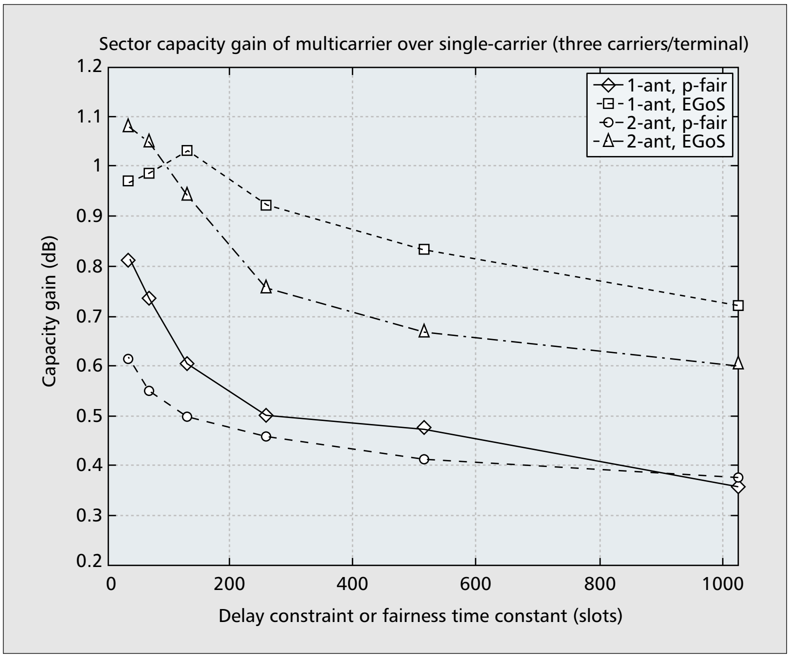

Figure 4. *Capacity gains due to channel frequency selectivity for multicarrier over single-carrier (16 terminals/sector, 3 carriers/terminal).*

REVERSE LINK

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

Figure 5 shows the reverse link sector capacity as a function of number of users per carrier with a two-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 multicarrier operation. Since multicarrier operation on the reverse link improves the reverse link transmit efficiency at high data rates, multicarrier 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.

DEPLOYMENT SCENARIOS

Two likely multicarrier EV-DO deployment scenarios are as follows:

- Overlay (additional carriers added to existing 1xEV-DO Revision A single-carrier deployments)

- Hybrid frequency reuse (frequency reuse 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 reuse of 1 by $K = 1$ and frequency reuse of 3 by $K = 3$. $(K = 1)^2$ implies two carriers with $K = 1$, and $(K = 1)^3$ implies three carriers with $K = 1$. Two-carrier operation is represented by 2x, and three-carrier operation by 3x.

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

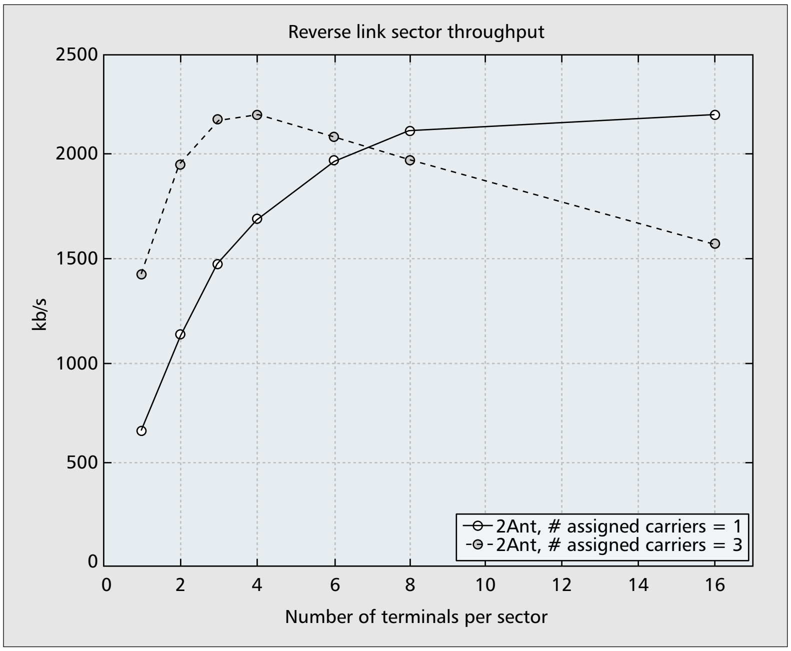

Figure 5. *Reverse link sector capacity for multicarrier operation.*

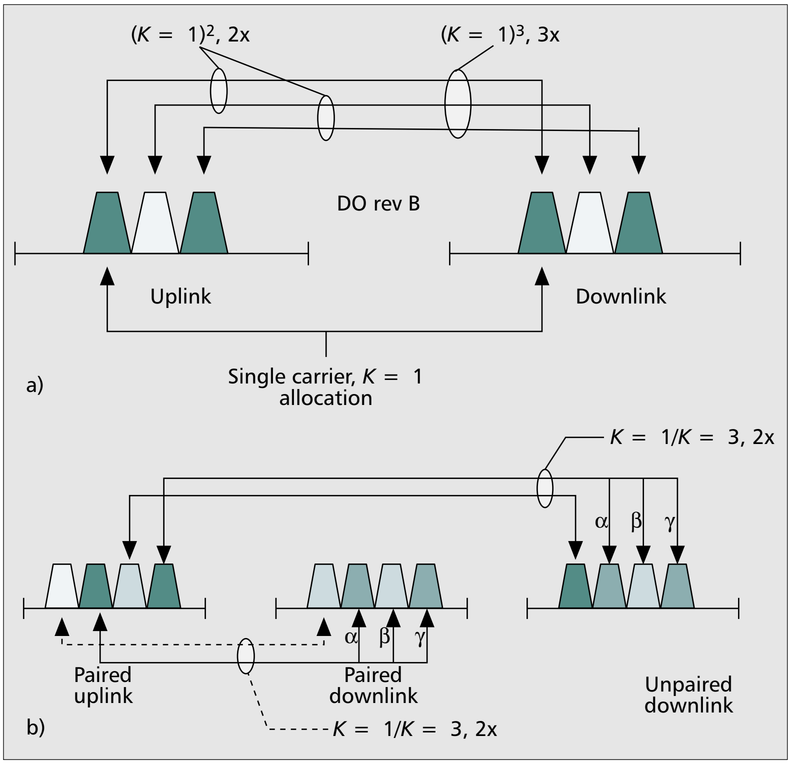

Figure 6. *Multicarrier EV-DO deployment scenarios.*

Hybrid frequency reuse is defined as the use of different frequency re-use for distinct sets of CDMA channels. For the example shown in Fig. 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 Fig. 6 (hybrid frequency reuse) is enabled by flexible duplex and multicarrier operation. α, β, and γ represent the sectors using the CDMA channel shown. Due to sector-based frequency reuse of 3, each sector only transmits one of the three frequencies from each frequency reuse set of 3.

In the hybrid frequency reuse 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.

Hybrid frequency reuse 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 four forward CDMA channels can be supported using the same hardware required for two forward CDMA channels using $K = 1$. $K = 3$ on the forward link results in improved SINR distribution, especially for users at cell edges, resulting in substantial improvement in the single-user throughput as shown in Fig. 7. This data is based on a network layout consistent with the 3GPP2 evaluation framework [2]. In Fig. 7, with $K = 1$ on one carrier with $K = 3$ for another carrier for hybrid frequency reuse, 2x deployment, we see that cell edge users observe a fourfold increase in throughput, and the peak data rate increased by 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 $K = 1$.

SUMMARY AND CONCLUSIONS

Multicarrier 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 reuse deployments in addition to overlays via the use of forward link frequency reuse and flexible duplex channel assignments.

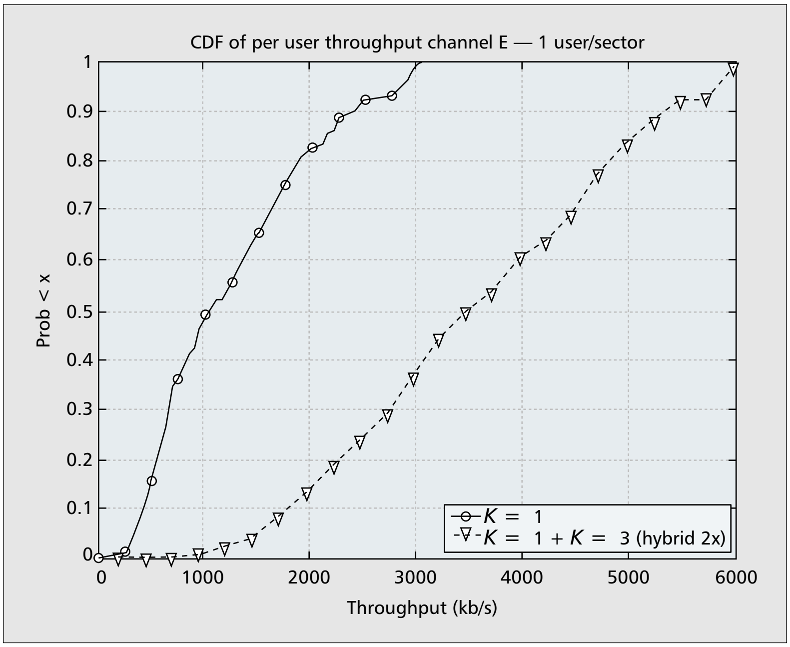

Figure 7. *CDF of single user throughput (K = 1 vs. K = 1 + K = 3, hybrid frequency reuse).*

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ADDITIONAL READING

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BIOGRAPHIES

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