Cellular Like Ad-hoc Networks: Smooth migration from ad-hoc networks towards cellular networks

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Abstract — **The deployment of cellular networks in private or office environments causes the problems of network planning and high initial installation costs. Before offering any service the locations of base stations have to be examined very well as later changes will be very cost intensive. Furthermore, the installation of base stations causes quite a lot of cabling to connect the base stations to the backbone network.**

Ad-hoc networks on the other hand offer immediate service, but with increasing network size their performance gets poor because the number of hops within the network increases. Furthermore, ad-hoc networks like IEEE 802.11 [1] and ETSI HIPERLAN Type 1 [2] have to use the same frequency channel in the same network thus limiting the network capacity.

The smooth migration path from an ad-hoc network to a cellular network prevents the initial costs of a cellular network by setting up an ad-hoc network first and replacing it by cellular components as it becomes feasible. The cost of the network installation thus grows with the users needs for services. Furthermore, it will be shown that the network capacity can be increased by using a hybrid network type, the so called *Cellular Like Ad-hoc Network* (CLAN).

I. Introduction

Many different types of ad-hoc networks have been presented in literature [3, 4, 5, 6]. The ad-hoc nature of the *Cellular Like Ad-hoc Network* (CLAN) is defined as if at least two terminals come into radio range with each other a communication between these two is possible and that the network is auto-configurable which means that the topology and connectivity of all nodes in the network is managed without user interaction.

The topology management includes the establishment of multihop connections beyond the radio range and the robustness against node failure. User connections are not disturbed by the inclusion of new nodes in the network or the shut down of single nodes (if possible).

This paper first defines the basic elements of CLANs and compares the network topology with cellular and ad-hoc networks (Section II). The main part of the paper focus on the network capacity offered by different network classes under different traffic distributions. Therefore, in Section III first an example for calculating the network capacity is given, followed by the derivation of general formulas and the discussion of them. Section IV shows the advantages of deploying CLANs. Some conclusions are drawn in Section V.

II. Cellular Like Ad-hoc Networks (CLAN)

Different from the nature of other ad-hoc networks like ETSI HIPERLAN/1 and IEEE 802.11 the nodes in CLAN are organized in clusters or subnetworks [7, 8]. Each subnetwork is controlled by a central instance the so called *Central Controller* (CC) [4]. Adjacent subnetworks work on different frequency channels in an FDM manner. The medium access within one subnetwork is characterized as load adaptive TDMA/TDD and is based on the upcoming HIPERLAN/2 specification [9, 10]. Thus each subnetwork is organized as in a cellular network which is the main focus of the HIPERLAN/2 standardization. The main difference however is that the central instance which replaces the base station of a cellular network is chosen during operation. This implies that every node is able to be the CC. As the CC is chosen dynamically it can be adopted to the current traffic load and network topology. Once a cellular network is installed it is hard to change the locations of the base stations or *Access Points* (AP).

In order to make most efficient use of CLANs the following additional functions have to be implemented in all nodes (or most of the nodes):

Central Controller (CC) Each node shall be able to act as a CC in order to choose the most appropriate one in the network. The tasks of the CC include the coordination of the medium access by organizing a MAC frame structure and granting capacity to the nodes of the subnetwork, and traffic management functions like call admission control and congestion control in order to prevent overload from the subnetwork.

Access Point (AP) An AP offers access to the fixed network. Depending on the type of core network different functions have to be supported. If the AP is controlled by a switch or router an *Access Point Control Protocol* (APCP) has to be implemented in the AP [11].

Forwarding Node (FN) In order to extend the service range beyond the radio range FNs perform a forwarding of data between two subnetworks. FNs are connected to two CCs but communicate with only one at a time. The FN collects data from one subnetwork and switches to the other one to deliver it in a time shared manner.

Auto-configuration Different from a basic cellular network the CLAN may change its configuration and all nodes must be able to participate in the auto-configuration process.

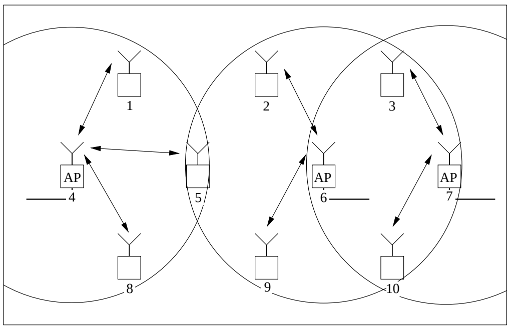

Figure 1: Example for a *Basic Cellular Network* (BCN)

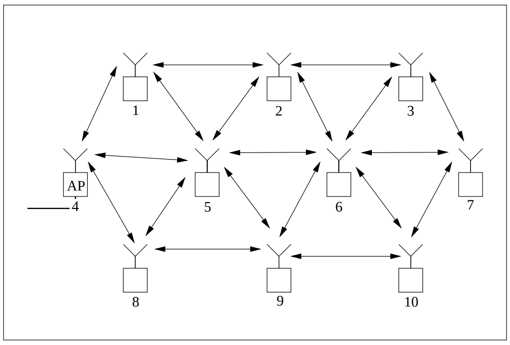

Figure 2: Example for a *Basic Ad-hoc Network* (BAN)

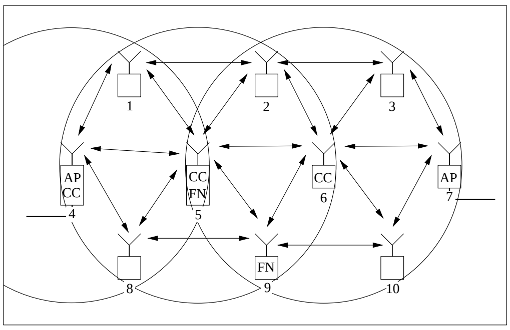

Figure 3: Example for a *Cellular Like Ad-hoc Network* (CLAN)

Another advantage of CLANs is their scalability as it is always possible to extend the service range by deploying more terminals. The drawback of CLANs is obvious; the CLAN nodes are more complex and therefore more expensive than ordinary network nodes.

In order to distinguish different network topologies, three classes are defined:

Basic Cellular Network (BCN) A basic cellular network is characterized by its cellular structure. APs provide access to the core network for nodes. No direct communication between two nodes is possible. Therefore, no communication is possible is case of the lack of infrastructure (base stations). Adjacent APs use different resources, e. g. different frequencies (in GSM), different FDM/TDM channels (in DECT), or different codes (in IS-95).

Basic Ad-hoc Network (BAN) A basic ad-hoc network is characterized by its distributed organisation. Only one type of terminal is in the network and all terminals are able to forward packets of other terminals. The medium access is controlled in a distributed manner. IEEE 802.11 is an important type of BAN. In BANs like IEEE 802.11 and ETSI HIPERLAN/1 all nodes belonging to the same network work on the same resource, e. g. the same frequency or the same hopping sequence. In other types of BANs a dynamic resource allocation protocol is used and only pairs of network nodes use the same resource [5, 6].

Cellular Like Ad-hoc Network (CLAN) Cellular like ad-hoc networks are characterized by a centrally organized network structure, but a distributed user plane. Network nodes are clustered and controlled by an CC. Direct communication between to nodes is possible under the control of the CC. CLANs use the same organisation of resources as BCNs. The CC is in charge of allocating an appropriate resource to the cluster.

Figures 1 - 3 show an example of the organisation of networks for the three classes. Figure 1 shows a BCN with three APs covering all network nodes. As no direct communication between terminals is foreseen in BCNs, the connectivity indicated by arrow is very limited for BCNs. Figure 2 shows a BAN with one AP as it may be deployed using IEEE 802.11 products. The connectivity is much higher than in Figure 1 but the number of hops to reach the AP as well[1]. Figure 3 shows a CLAN with two APs which is a sort of overlay build from Figure 1 and 2. Only the locations of the CCs differ from those of the APs in the BCN. In CLANs an AP does not have to be a CC as well, therefore the locations of the CCs can be optimized independent from the locations of the APs. In Figure 3 the number of APs is lower than in Figure 1 but higher than in Figure 2. The connectivity is the same as for BAN, but the number of hops to reach an AP is lower.

Furthermore, Figure 3 shows possible locations of *Forwarding Nodes* (FN) which forward data packets from one subnetwork (indicated by circles) to the adjacent one. CCs can always act as forwarder within a subnetwork.

III. Network Capacity Calculation

The network capacity is defined as the capacity which is available for each connection and/or node in the network. The parameters which influence the network capacity apart from the topology are:

- Number of hops per connection
- Number of available frequencies
- Traffic distribution

[1] In BCN the number of hops is always one.

In order to calculate the network capacity analytically two simple traffic distributions have been assumed:

1. The traffic is distributed uniformly among all network nodes. This means that every node has one connection to each other node in the network. This is denoted as *intra network traffic* (INT).
2. All nodes communicate to the core network. This means that every node has one connection (bidirectional) to the closest AP. This is denoted as *core network traffic* (CNT).

Real traffic distributions will be a mixture of intra and core network traffic. Furthermore, different nodes will have different traffic requirements.

For the calculation the following assumptions have been made:

- One frequency channel is used per AP or CC. The number of frequency channels for the BAN is set equal to the number of CCs in the CLAN.
- The capacity per frequency channel is 20 Mbit/s.

First the network capacity for the network topology examples given in Figures 1 - 3 will be calculated. Afterwards general formulas are given for the network capacity.

A. Capacity example

Basic Cellular Networks In case of uniformly distributed traffic the radio cell on the left hand with one AP and three MTs is the limiting cell in terms of network capacity (Figure 1).

Assuming intra network traffic, each MT runs 9 up- and 9 downlink connections to reach all other nodes (including the APs). This sums up to a total of 54 connections in this radio cell. If the total capacity of the radio cell is 20 Mbit/s the capacity per connection is $C_{C,INT,BCN} = \frac{20\ Mbit/s}{54} = 370\ kbit/s$.

The case of core network traffic is very simple; each MT runs 1 up- and 1 downlink connection. Thus 6 connections in the radio cell leads to a capacity per connection of $C_{C,CNT,BCN} = \frac{20\ Mbit/s}{6} = 3.3\ Mbit/s$.

Basic Ad-hoc Network In order to calculate the capacity for BANs the number of hops has to be counted for each single node. As the network has a symmetry four classes of terminals with the same number of hops to the other nodes can be identified (Figure 2).

Table 1: Number of hops for the BAN in Figure 2

Nodes	4,7	1,3,8,10	2,9	5,6
Hops	18	17	14	12

Table 1 shows the number of hops every node needs to reach each other node in the given network. Considering bidirectional connections the total number of hops sums up to 156. Assuming an optimum channel allocation scheme and three frequency channels with 20 Mbit/s each, the capacity per connection is $C_{C,INT,BAN} = \frac{3 \cdot 20\ Mbit/s}{156} = 385\ kbit/s$.

In case of core network traffic the capacity for BANs is limited by two factors, the capacity of the AP(s) and the capacity within the network (number of hops to reach the AP(s)). Considering the example given in Figure 2 the mean number of hops to reach the AP is 2. This sums up to 36 hops considering up- and downlink. Serving 36 hops with the given frequencies gives a capacity per connection of 1.67 Mbit/s. On the other hand the AP has to handle 18 connections (up- and downlink to each node). Running at 20 Mbit/s (one transceiver only) the capacity per connection is limited to $C_{C,CNT,BAN} = \frac{20\ Mbit/s}{18} = 1.1\ Mbit/s$.

Cellular Like Ad-hoc Network Calculating the capacity of the CLAN in Figure 3 for intra network traffic the number of hops is given in Table 2. It has to be noted that different from Figure 2 here two APs are connected via the core network and it is assumed that traffic is routed via the core network if appropriate. Thus node 1 can reach node 7 (AP) with one radio hop to node 4 (AP) and then via the core network to node 7 (AP). This counts as one hop only.

Table 2: Number of hops for the CLAN in Figure 3

Nodes	4,7	1,3,8,10	2,9	5,6
Hops	10	14	14	11

With bidirectional connections the total number of hops sums up to 126. This is exactly the same number of hops as for the BCN example ($2 \cdot 7 \cdot 9$). With the CCs in the given position the capacity can be allocated in a way that the traffic is uniformly distributed among the network due to the high connectivity. Thus the capacity per connection is $C_{C,INT,CLAN} = \frac{3 \cdot 20\ Mbit/s}{126} = 476\ kbit/s$.

For core network traffic only nodes 2 and 9 have to be considered separately as all other nodes are within a one hop distance to an AP. Assuming AP traffic is controlled by node 4 (AP+CC) and node 6 (CC), node 5 (CC) is able to handle the forwarding of node 2 to node 5 and node 9 to node 6. As node 5 works on a different frequency, this does not limit the total network capacity. Each AP has to handle four (virtual) nodes thus 8 connections have to be considered (4 up- and 4 downlink) per frequency channel. This leads to a capacity per connection of $C_{C,CNT,CLAN} = \frac{20\ Mbit/s}{8} = 2.5\ Mbit/s$.

Comparison From this example the following conclusions can be drawn. In BCNs even intra network traffic is mostly carried via the core network. The capacity of BCNs is limited by the number of APs and the distribution of MTs among APs. In BANs the capacity is limited by the number of hops and in case of core network traffic by the capacity of the AP(s).

As in CLANs the location of CCs can be freely chosen it can be optimized. For INT this gives the highest capacity as CLANs profit from both, high connectivity and core network connections for the APs. For CNT CLANs are mainly limited by the number of APs and less by the distribution of MTs as the number and location of CCs can be optimized for different MT distributions. Thus deploying as many APs as in BCNs gives always at least the same capacity as in BCNs.

Table 3: Comparison of capacity per connection

	INT [kbit/s]	CNT [Mbit/s]
BCN	370	3.3
BAN	385	1.1
CLAN	476	2.5

B. General Network Capacity

The general network capacity will be calculated for the two traffic distributions INT and CNT with the following assumptions:

- Enough frequency channels are available for a reuse partition of 12 which equals 12 frequency channels are available to the network under investigation.
- Minimum coverage is given with 12 APs or CCs.
- The network nodes are uniformly distributed in a circle area with a radius R. The total number of network nodes is denoted as N_{node}.

Basic Cellular Networks The capacity of BCNs is limited by the number of APs (N_{AP}) and thus the maximum number of nodes per AP ($\rho_{AP} = \lceil \frac{N_{node}}{N_{AP}} \rceil$ for uniformly distributed nodes). For INT and CNT the capacity per connection is given by:

$$C_{C,INT,BCN} = \frac{C_f}{\rho_{AP}(2N_{node} - \rho_{AP} - 1)} \quad (1)$$

and

$$C_{C,CNT,BCN} = \frac{C_f}{2 \cdot \rho_{AP}} \quad (2)$$

Basic Ad-hoc Network The capacity in case of CNT is limited by two factors, the capacity of the AP(s) and the capacity within the network. Assuming one AP services an area of the radius R, the mean number of hops from the AP to all other nodes is given by:

$$\overline{N_{hop,CNT,BAN}} = \frac{\sum_{i=1}^{R}(2 \cdot i - 1) \cdot i}{R^2} \quad (3)$$

As bidirectional traffic is considered, the capacity per connection is limited by the AP:

$$C_{C,CNT,BAN,1} = \frac{C_f}{2 \cdot N_{node}} \quad (4)$$

and limited by the network (assuming N_f frequencies to operate $\hat{=} N_f$ simultaneous transmissions):

$$C_{C,CNT,BAN,2} = \frac{N_f \cdot C_f}{2 \cdot \overline{N_{hop,CNT,BAN}} \cdot N_{node}} \quad (5)$$

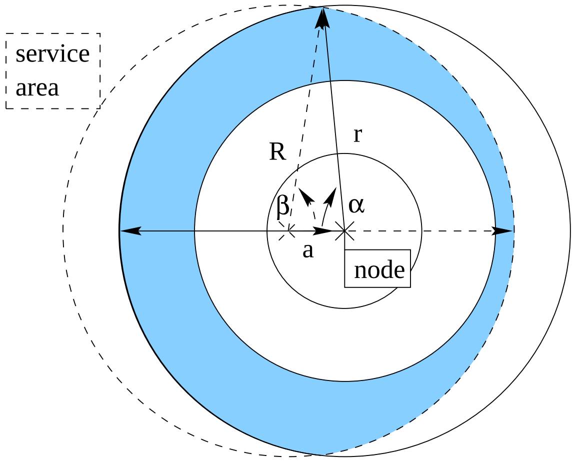

Figure 4: Definition of parameters in the BAN

The minimum of equation (4) and (5) is the resulting capacity for CNT.

For INT the number of hops from every node to each other node has to be calculated. For the node in the centre this is equal to (3). For a node which is in a distance of a to the centre the mean number of hops can be calculated as follows:

If r denotes the actual hop radius, A_r denotes the service area up to the hop distance of r. A_{r-1} therefore denotes the service area up to the hop distance of $r-1$. The grey area in Figure 4 shows $A_r - A_{r-1}$ for $r = 3$. Now A_r is calculated by integrating over r for an angle of α and over R for an angle of β:

$$\begin{aligned} A_r &= \pi r^2 && (6)\\ \text{for} &\quad 0 < r \leq s \\ A_r &= 2 \cdot \int_0^{\alpha} r^2 \cdot sin^2 x\, dx + && (7)\\ & \quad 2 \cdot \int_0^{\beta} R^2 \cdot sin^2 x\, dx \\ \text{for} &\quad s < r < t \\ A_r &= \pi R^2 && (8)\\ \text{for} &\quad r = t \\ \text{with} \\ \alpha &= arccos \frac{r^2 + a^2 - R^2}{2 \cdot r \cdot a} && (9)\\ \beta &= arccos \frac{R^2 + a^2 - r^2}{2 \cdot R \cdot a} && (10)\\ s &= \lfloor R - a \rfloor && (11)\\ t &= \lceil R + a \rceil && (12) \end{aligned}$$

So the mean number of hops for a node in a distance a to the centre is given by:

$$\overline{N_{hop,a}} = \frac{\sum_{i=1}^{t} i(A_i - A_{i-1})}{\pi \cdot R^2} \quad (13)$$

For the mean number of hops of the total network $N_{hop,a}$ has to integrated over $0 \leq a \leq R$:

$$\overline{N_{hop}} = \frac{\int_0^R a \cdot \overline{N_{hop,a}}\, da}{R^2} \quad (14)$$

Thus the capacity per connection is given by:

$$C_{C,INT,BAN} = \frac{N_f \cdot C_f}{\overline{N_{hop}} \cdot N_{node} \cdot (N_{node} - 1)} \tag{15}$$

Cellular Like Ad-hoc Network The capacity for CLAN depends on the number of CCs and APs. If $N_{CC} = N_{AP}$ then $C_{C,CNT,CLAN} = C_{C,CNT,BCN}$ and $C_{C,INT,CLAN} \geq C_{C,INT,BCN}$, because CLAN supports direct communication within a cluster. If $N_{AP} = 1$ then $C_{C,CLAN} = C_{C,BAN}$ for both INT and CNT.

If several cluster are served by one AP, the capacity depends on the cluster size $cs = \frac{N_{CC}}{N_{AP}}$ [2]:

$$\overline{N_{hop,cs}} = 2 - \frac{1}{cs} \quad for \quad cs \leq 7 \tag{16}$$

$$C_{C,CNT,CLAN} = \frac{cs \cdot C_f}{2 \cdot N_{hop,cs} \cdot N_{node,cs}} \tag{17}$$

with $N_{node,cs} = \frac{N_{node}}{N_{AP}} \cdot cs$.

For INT two classes of nodes have to be differentiated, nodes within the range of an AP and node outside the range of an AP. Figure 5 shows the relations in the CLAN cluster. Each cell with an AP is surrounded by cells without APs. The maximum number of hops to reach one AP is 2. The dark cell indicates that each cell can reach 6 other cell within two hops.

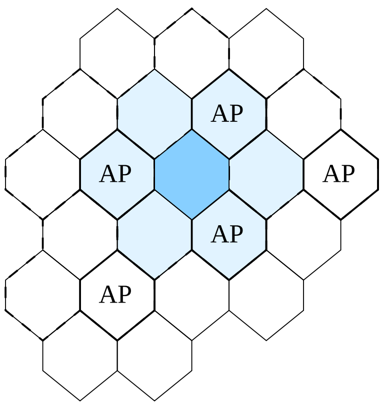

Figure 5: Clusters in CLAN, cluster size 3

With the density $\rho_{CC} = \frac{N_{node}}{N_{CC}}$ of nodes per CC, the mean number of hops of the two classes is given by:

$$\overline{N_{hop,AP}} = \frac{2 \cdot N_{node} - \rho_{AP} - 1}{N_{node} - 1} \tag{18}$$

$$\overline{N_{hop,NAP}} = \frac{3 \cdot N_{node} - 8 \cdot \rho_{AP} - 1}{N_{node} - 1} \tag{19}$$

The weight of both groups is given by the number of APs (N_{AP}) and the number of cells without AP ($N_{CC} - N_{AP}$):

$$\overline{N_{hop}} = \frac{N_{AP} \cdot \overline{N_{hop,AP}} + (N_{CC} - N_{AP}) \cdot \overline{N_{hop,NAP}}}{N_{CC}} \tag{20}$$

[2]it is assumed that APs are not CCs

Thus the capacity per connection is given by:

$$C_{C,INT,CLAN} = \frac{N_f \cdot C_f}{\overline{N_{hop}} \cdot N_{node} \cdot (N_{node} - 1)} \tag{21}$$

C. Discussion

In order to compare the capacity of BCN, BAN and CLAN for CNT and INT, the capacity is calculated for different number of network nodes and a service area with a radius of $R = 2$. The cluster size for CLAN is set to 1 and 3 resulting in 12 and 4 APs in the service area under consideration.

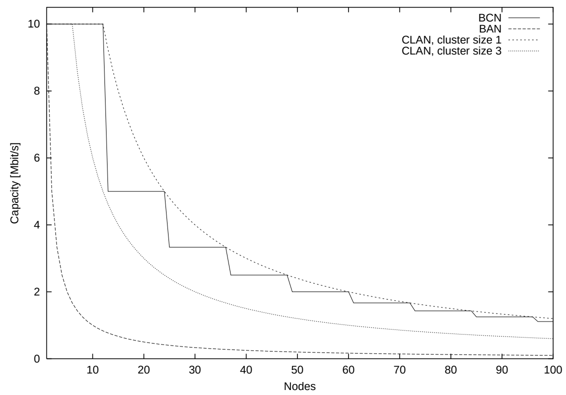

Figure 6: Network capacity assuming core network traffic

Figure 6 shows the capacity per connection for CNT. It is obvious that BCN offers the highest and BAN the lowest capacity (limited by the one AP). The capacity for CLAN for a cluster size of 3 is in between. With only one third of the APs CLAN reaches about one half of the capacity of BCN. Thus the capacity per AP is higher. With a cluster size of 1 the capacity of CLAN is higher, because CLAN can distribute the traffic within the network better than BCN (this requires $N_{CC} > N_{AP}$).

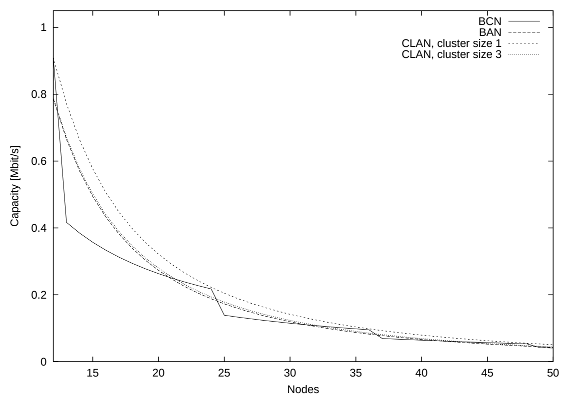

Figure 7: Network capacity assuming intra network traffic

Figure 7 shows the capacity per connection for INT. The differences between the networks are quiet low. CLAN again offers the highest possible capacity, because it benefits from the direct communication between nodes within one cell. The capacity of BCN strongly depends on the distribution of nodes among APs.

IV. Smooth migration from ad-hoc networks towards cellular networks

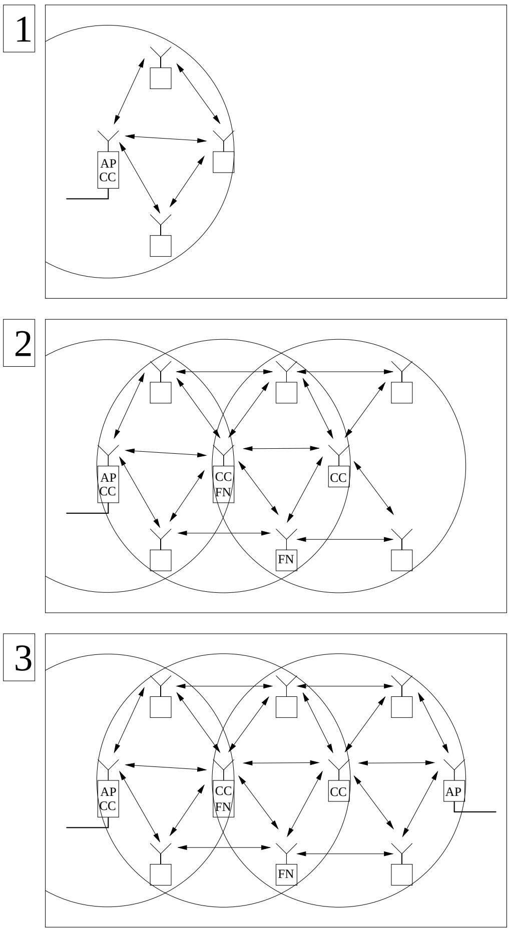

Figure 8: Smooth migration from ad-hoc networks towards cellular networks

The basic idea of CLANs is that they are able to combine the advantages of ad-hoc and cellular networks. With deploying CLANs in an ad-hoc manner immediate service is possible while the capacity can be increased later by connecting terminals to the fixed network. The terminals them self can indicate via a user interface which connection to the fixed network is most efficient, thus the task of network planning is simplified. The following deployment steps are possible with a CLAN:

1. Installation of a single AP connected to the core network offering initial service around this AP (Figure 8, 1).
2. Deployment of terminals around the AP which increase the service area step-by-step. The more terminals are deployed the larger the services area will grow (Figure 8, 2).
3. Connecting appropriate terminals to the core network thus making them APs (Figure 8, 3).

Figure 8 shows the steps of migration. CLANs first work like *Basic Ad-hoc Networks* (BAN) with an AP, but if the network capacity is exhausted by too many multihop connections the capacity can be increased by connecting terminals to the core network. In the final state the capacity is at least as high as in *Basic Cellular Networks* (BCN). Thus CLANs adapt there network topology to the needs of the users.

V. Conclusions

Cellular Like Ad-hoc Networks (CLANs) offer the capability of both, cellular and ad-hoc networks. As shown in the network capacity calculations the offered capacity of CLANs depends on the number of APs spent in the network. If the same number of APs is used as in cellular networks the capacity of CLAN is higher due to the possibility of direct communication. Furthermore, even without any APs operation is possible.

The potential of CLANs is high and has to be investigated more intensively. Especially the organisation of CLANs including CCs and forwarding nodes has to be studied in more detail.

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